Radiology: Cardiothoracic Imaging

IMAGING ESSAY

Lung Ultrasound: The Essentials

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Conflicts of interest are listed at the end of this article.

Radiology: Cardiothoracic Imaging 2021; 3(2):e200564 • https://doi.org/10.1148/ryct.2021200564 • Content codes: CH US

Although US of the lungs is increasingly used clinically, diagnostic radiologists are not routinely trained in its use and interpretation. Lung US is a highly sensitive and specific modality that aids in the evaluation of the lungs for many different abnormalities, including pneumonia, pleural effusion, pulmonary edema, and pneumothorax. This review provides an overview of lung US to equip the diagnostic radiologist with knowledge needed to interpret this increasingly used modality.

Supplemental material is available for this article.

Lung US has dramatically increased in popularity over the last decade and is routinely performed at the patient's bedside, especially in the emergency department and the intensive care unit (ICU) (1–3). Formal training in the performance and interpretation of lung US, however, is not a traditional component of radiology residency education in the United States. As this modality becomes an imaging staple, the diagnostic radiologist should be fluent in lung US performance and interpretation to maintain relevance and assist the ordering clinician. In this imaging essay, the essentials of lung US are described and radiographic correlation for lung US imaging findings on chest radiographs and chest CT images is provided. A discussion of the role of lung US in health care delivery and the future directions of lung US is also included.

Utility of Lung US

Lung US is radiation-free, low-cost, rapid, and portable, allowing real-time examination of pulmonary structures. Meta-analyses suggest that compared with chest radiography, lung US may have higher sensitivity and similar specificity for detection of pleural effusion, pneumonia, pneumothorax, and pulmonary edema (Table) (4–7). It is increasingly used in the ICU to detect these diseases. Critical care providers have adopted the bedside lung US in emergency (BLUE) protocol as a standardized approach to lung US in the ICU. This protocol can be performed in less than 3 minutes at the bedside and has a diagnostic accuracy greater than 90% for asthma and/or chronic obstructive pulmonary disease, pneumonia, pneumothorax, pulmonary edema, and pulmonary embolism (1,8). The accuracy for pulmonary embolism derives from the protocol directing the provider to examine the deep venous structures if there is no sign of pulmonary disease. Many practitioners have advocated for the regular use of lung US in the ICU to decrease the use of chest radiography, which is associated with increased cost and nontrivial cumulative radiation exposure (especially in pediatric patients) (9–17). Lung US also has a well-established role in guiding interventional procedures, including thoracentesis and biopsy, and has been shown to improve outcomes in these procedures by reducing complications (eg, pneumothorax) (18,19). Finally, lung US has a special role in pediatrics, including improved visualization of abnormalities in the thorax owing to the small thoracic diameters of children and the lack of ionizing radiation to produce diagnostic imaging results (11,20–31).

The limitations of lung US should also be noted when considering its general utility. Lung US is operator dependent, and its quality varies by practitioner. Advanced technical skill and clinical knowledge of the operator increase diagnostic yield; however, studies have shown that the rudimentary skills of the modality can be learned with relative ease (32–34). A limitation of lung US compared with chest radiography is the time needed to perform the examination. Depending on the thoroughness of the examination, complete lung US can take 20 minutes to perform, whereas chest radiography can be completed in a few minutes (9,28). Another limitation in lung US is that findings such as A-lines and B-lines can be seen in a variety of conditions (1,2,14,35). For example, in pediatric patients with bronchiolitis, studies have shown the lung US findings of atelectasis and pneumonia overlap (22,25,36). However, this is not a problem unique to US, as similar issues with specificity exist with both chest radiography and, to a lesser extent, with CT. Lung US is predominantly an artifact-based imaging modality, typically visualizing only abnormalities abutting the pleural line as discussed herein in the Physics of Lung US section (2,35,37). For a complete examination of the deeper thoracic structures, chest radiography and/or CT imaging are preferred. Similarly, in the ICU, lung US is more limited in evaluating lines

Abbreviations

BLUE = bedside lung US in emergency, ICU = intensive care unit

Summary

Compared with chest radiography, lung US may have higher sensitivity for detection of pleural effusion, pneumonia, pneumothorax, and pulmonary edema. It is increasingly used in the intensive care unit to detect these conditions.

Key Points

- US of the lungs is increasingly being used clinically and is simple to learn, perform, and interpret.
- Lung US is predominantly artifact-based as opposed to most US examinations, which allow direct visualization of the target region of interest. At lung US, the A-line artifact is seen in air-filled lung, the B-line artifact is seen in conditions such as pulmonary edema and/or fibrosis, and consolidation and effusion are directly visualized.
- Meta-analyses suggest that lung US has higher sensitivity with similar specificity compared to chest radiography for some pulmonary conditions, including pneumonia, pleural effusion, and pulmonary edema.

and tubes compared with chest radiography. Thus, rather than being rival modalities, chest radiography and lung US function as complementary modalities that can be used in conjunction to benefit patient care.

Image Acquisition at Lung US

Complete lung US involves examining each hemithorax in the anterior, lateral, and posterior lung zones (Fig 1) (35,38). All lung fields should also be examined in transverse and longitudinal orientations, as failure to include both orientations may lead to missed abnormalities (39). The patient may be imaged in both the supine and upright position. As with all US examinations, proper technique is essential to ensure adequate imaging. Because much of lung US is artifact based, the probe must be held perpendicular to the skin to ensure perpendicular orientation to the pleural line to produce the requisite artifacts for interpretation. In addition, larger body habitus may limit evaluation of the pleural line as well as structures at depth. A variety of probes may be used in this application depending on the patient's age and the indication for the examination (35). Curvilinear or phased-array 5–9-MHz probes are well equipped to examine the lung. Linear 7–12-MHz probes offer the best resolution of superficial structures and are especially useful in children (low thoracic diameter) and for assessing pneumothorax. In the point-of-care setting, lung US may be abbreviated and tailored to only transverse and sagittal views of the area of interest. Contrast-enhanced US of the lungs has been investigated and may provide additional benefit to assess peripheral pulmonary lesions and guide biopsies (40–44). Color Doppler US has an established role in the evaluation of abscess and empyema as well as a lesser known role in the evaluation of pneumothorax (37,45–49). Some evidence also suggests that Doppler US can be helpful in distinguishing benign and malignant peripheral lung lesions, but this is somewhat controversial (37,46,50–52).

Physics of Lung US

The physics of lung US is complicated and is briefly summarized here in simple terms. Lung US is unique among other US examinations, because it is predominantly artifact based, in contrast to other US examinations in which anatomy is directly visualized. Most ultrasound waves are reflected at the pleura in an air-filled lung owing to the acoustic impedance mismatch at the air and soft-tissue interface that results in a hyperechoic pleural line (53). Thus, the air-filled lung parenchyma cannot be directly visualized at US. Instead, A-line artifacts, which are horizontal reverberation artifacts of the hyperechoic pleural line, are reflected from the air-filled lung, allowing the observer to infer its existence (Fig 2). When the lung interstitium is thickened (ie, pulmonary edema, interstitial inflammation and/or infection, or pulmonary fibrosis), B-line artifacts (hyperechoic vertical lines traversing the imaging field below the pleural line) replace the normal A-lines (Fig 2). The physics of B-lines is not entirely understood (54–57). Lung collapse or consolidation removes the A-line artifact and allows for direct visualization of the parenchyma (Fig 2). Pleural effusions, both complex and simple, are also directly visualized. If a pulmonary abnormality does not touch the pleural line, it is not visualized owing to the acoustic impedance mismatch between the air and soft-tissue interface. The majority of clinically significant abnormalities, especially life-threatening abnormalities, typically abuts the pleural line, therefore permitting its detection at US (1).

Radiographic Correlation of Lung US Findings

Air-Filled Lung

The A-line artifact predominates in normal air-filled lungs (Fig 3) (1,35). In addition, during respiration the sliding visceral and parietal pleura is visualized as shimmering motion of the pleural line, referred to as *lung sliding* (Movies 1 and 2). Pathologic conditions with air-filled lungs also have A-line artifacts; these conditions include asthma, chronic obstructive pulmonary disease, mild viral illness, and pulmonary embolism without focal infarct. In suspected pulmonary embolism, in which A-lines predominate, a US examination of the deep venous structures can be performed (1,35). In addition, if a pulmonary infarct is present, it will appear as a consolidation abutting the pleural surface (46).

Interstitial Thickening: Edema and Fibrosis

When the pulmonary interstitium thickens (secondary to fibrosis or fluid), B-line artifacts replace the normal A-lines (1,35). B-line artifact consists of well-defined, laserlike, vertical, echogenic lines arising from the pleural line and extending to the bottom of the image. Scattered B-lines (fewer than two per intercostal space) can be present in normal lung (2,56). The number of B-lines directly correlates to disease

Sensitivity and Specificity of Lung US versus Chest Radiography

			Lung US		Chest Radiography	
Indication	Study Type	No. of Patients	Sensitivity (%)	Specificity (%)	Sensitivity (%)	Specificity (%)
Pleural effusion (5)	Prospective	32	92	93	39	85
Pneumonia (7)	Systematic review with meta-analysis	742	95	90	77	91
Pneumothorax (4)	Systematic review with meta-analysis	5314	87	99	46	100
Pulmonary edema (6)	Systematic review with meta-analysis	1827	88	90	73	90

Note.—Sensitivity and specificity values vary slightly from study to study. The pleural effusion statistics are drawn from a sample of critically ill patients.

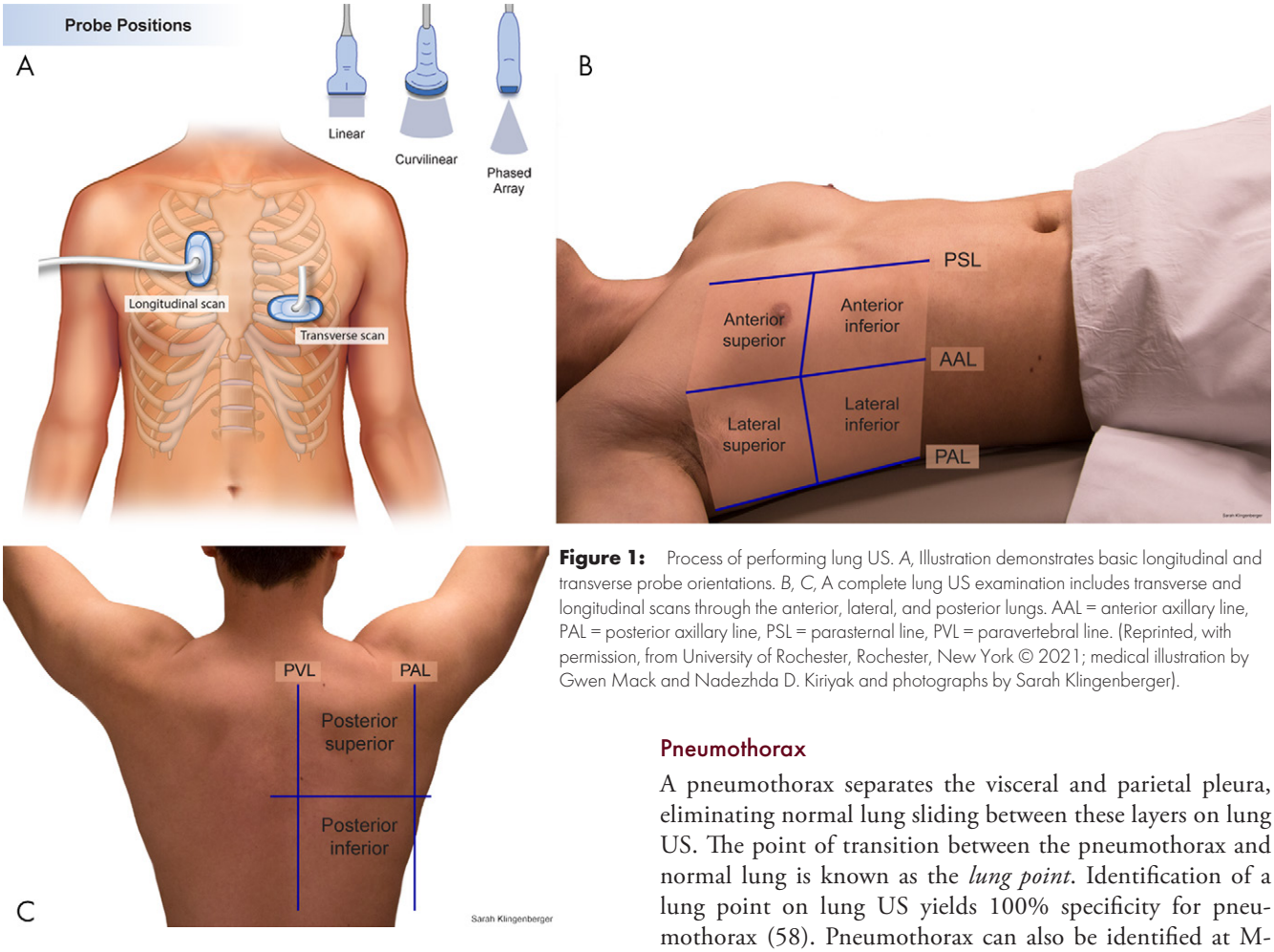

Figure 1: Process of performing lung US. *A*, Illustration demonstrates basic longitudinal and transverse probe orientations. *B, C*, A complete lung US examination includes transverse and longitudinal scans through the anterior, lateral, and posterior lungs. AAL = anterior axillary line, PAL = posterior axillary line, PSL = parasternal line, PVL = paravertebral line. (Reprinted, with permission, from University of Rochester, Rochester, New York © 2021; medical illustration by Gwen Mack and Nadezhda D. Kiriyak and photographs by Sarah Klingenberger).

severity. B-lines are diffusely present in the setting of pulmonary edema, pulmonary fibrosis, and pneumonitis (including vaping injury) (Figs 4 and 5) (Movies 3 and 4). The presence of B-lines on US is sensitive for pulmonary edema and may be more sensitive compared to chest radiography for its detection (6). Focal and/or unilateral B-lines suggest a localized process such as atypical pneumonia.

Pneumothorax

A pneumothorax separates the visceral and parietal pleura, eliminating normal lung sliding between these layers on lung US. The point of transition between the pneumothorax and normal lung is known as the *lung point*. Identification of a lung point on lung US yields 100% specificity for pneumothorax (58). Pneumothorax can also be identified at M-mode US, a technique that depicts motion. In a healthy lung, the tissue superficial to the pleural line remains stationary, with smooth horizontal lines at M-mode imaging. Deep to the pleura, the lung motion interrupts the lines, creating a finely interrupted granular or "sandy" pattern. This normal pattern is called the *seashore sign* as it depicts the boundary between the stationary chest wall ("ocean") and moving lung ("sand") (Fig 6). When a pneumothorax is examined at M-mode US, the smooth horizontal lines are uninterrupted, as

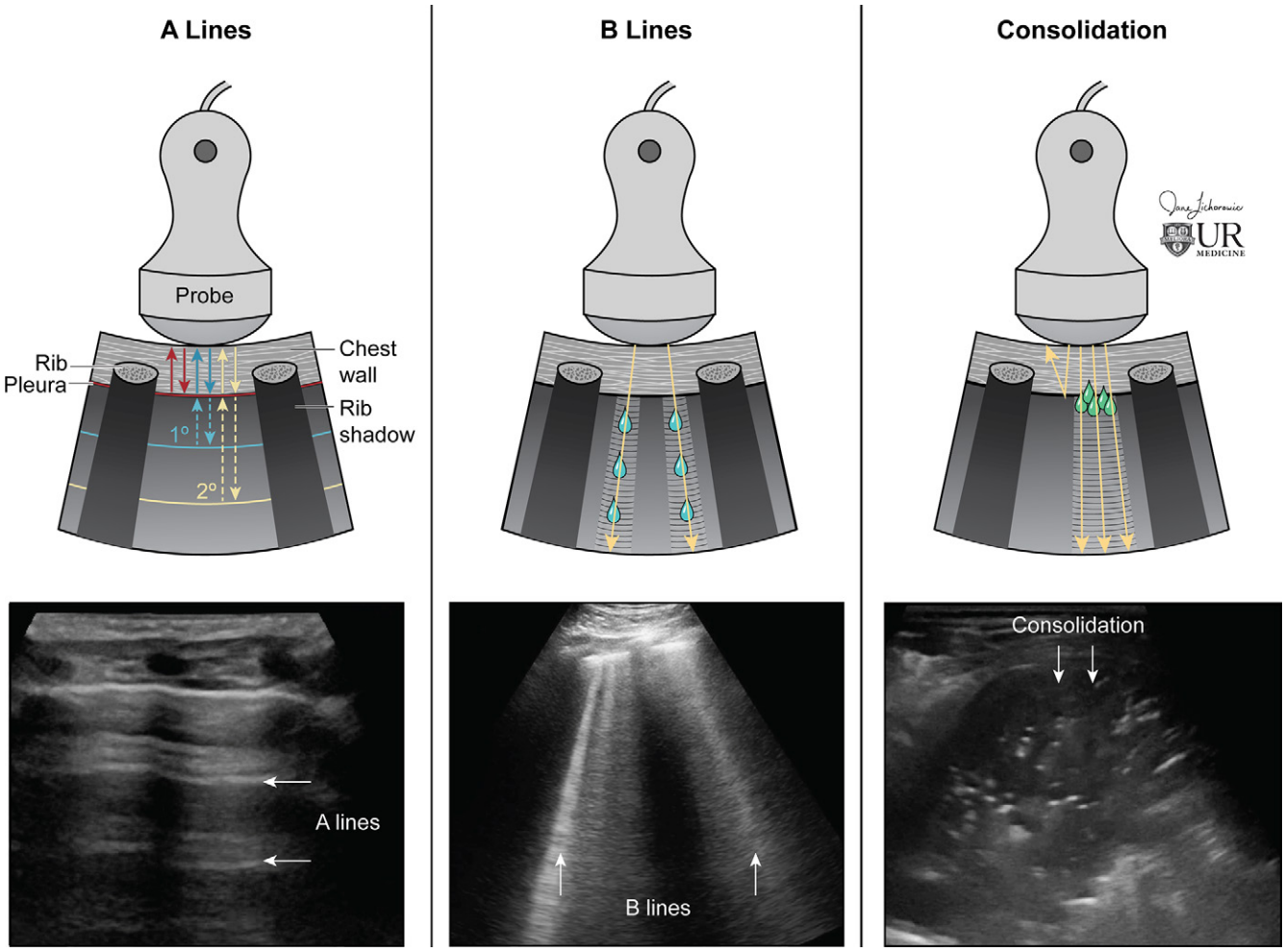

Figure 2: Physics of lung US. (Left) Ultrasound waves reflected at the pleural line creating A-line reverberation artifacts. (Center) As the interstitium thickens, the artifact pattern changes, with B-line artifacts obliterating A-lines. B-lines are hyperechoic vertical artifacts arising from the pleural line extending to the bottom of the field of view. (Right) Consolidation is directly penetrated by US, resulting in visualization without artifact if the consolidation is touching the pleural line. (Reprinted, with permission, from University of Rochester, Rochester, New York © 2021; medical illustration by Jane Lichorowic).

the chest wall and air deep to the pleura are both stationary in pneumothorax (1). This appearance of pneumothorax at M-mode examination has been dubbed the *bar code sign* (Fig 7) (Movies 5 and 6). Lung US surpasses chest radiography in sensitivity for pneumothorax (Table) (4). The addition of color Doppler US can improve detection of pneumothorax, as color signal from the lung is absent owing to the air barrier of the pneumothorax (48).

Pleural Effusion

US directly images pleural fluid (59). Simple effusions commonly present as anechoic fluid in the posterior dependent lung (1,5,35,49). Complex pleural fluid collections, including chronic effusions, malignant effusions, hemithorax, and empyema, are more heterogeneous in appearance on US depending on extent of debris, septations, and pleural thickening. Given the ability to visualize this level of detail, lung US is often better than conventional chest radiography for assessing complicated pleural effusions and assists in interventional management. Lung US can help to identify loculated areas for drainage or indicate the need for more aggressive therapy, including surgical washout or tissue plasminogen activator administration. A large effusion creates an acoustic window, allowing visualization of the vertebral bodies, also known as the *spine sign* (Fig 8).

Infection

Lung US is an excellent modality to evaluate and monitor known or suspected pulmonary infection (7,20,28,30,60–62). Pneumonia has several imaging appearances depending on the extent of consolidation or interstitial involvement (1,5,7,35). A completely consolidated lung mimics the solid appearance of the liver; this is known as *hepatization* (Fig 9) (Movies 7 and 8). In consolidation, fluid or cells fill the alveoli, and the normal A-lines or air-filled lung are lost. If air bronchograms are present, they are manifested as hyperechoic foci within the consolidated lung (Fig 9, *B*). The interface between consolidated abnormal lung and aerated normal lung is identified by an irregular hyperechoic line termed the *shred sign* (Fig 9, *C*). Smaller infections may manifest as a focal subpleural hypoechoic area. In early infection, focal B-lines may be present, indicating that the affected interstitium

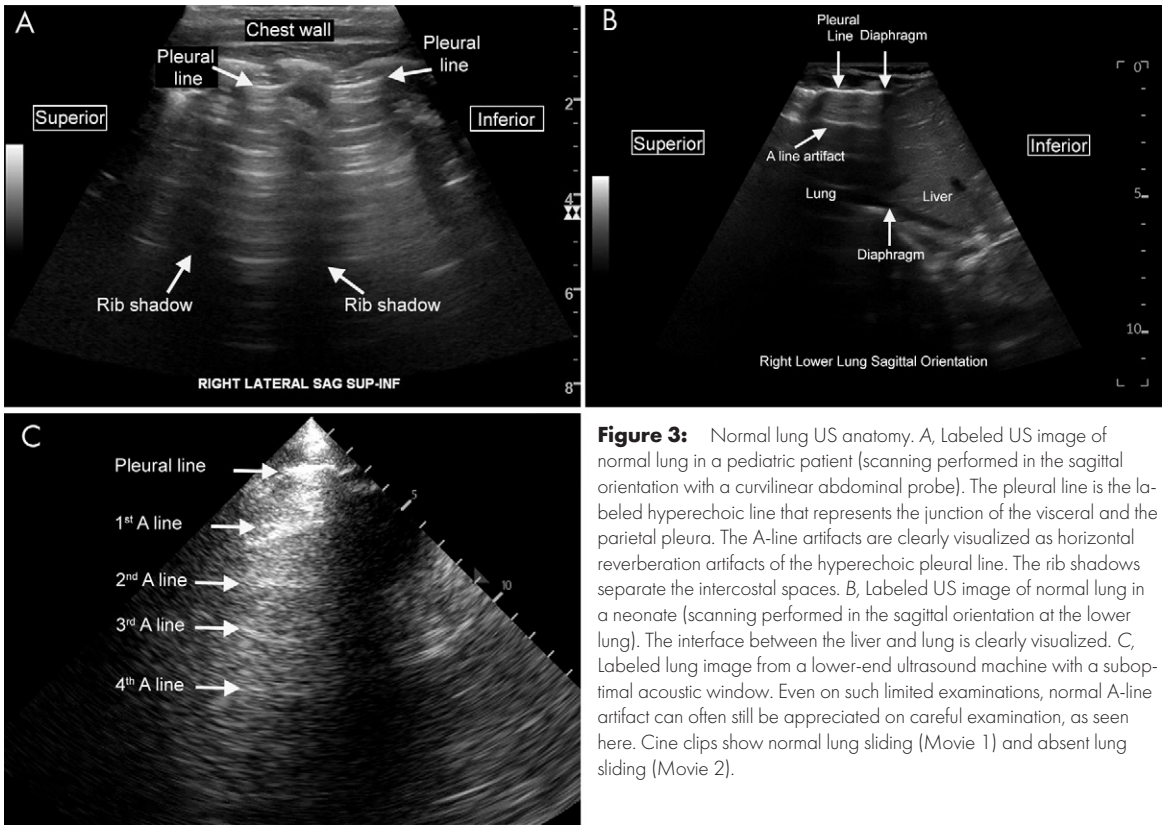

Figure 3: Normal lung US anatomy. *A*, Labeled US image of normal lung in a pediatric patient (scanning performed in the sagittal orientation with a curvilinear abdominal probe). The pleural line is the labeled hyperechoic line that represents the junction of the visceral and the parietal pleura. The A-line artifacts are clearly visualized as horizontal reverberation artifacts of the hyperechoic pleural line. The rib shadows separate the intercostal spaces. *B*, Labeled US image of normal lung in a neonate (scanning performed in the sagittal orientation at the lower lung). The interface between the liver and lung is clearly visualized. *C*, Labeled lung image from a lower-end ultrasound machine with a suboptimal acoustic window. Even on such limited examinations, normal A-line artifact can often still be appreciated on careful examination, as seen here. Cine clips show normal lung sliding (Movie 1) and absent lung sliding (Movie 2).

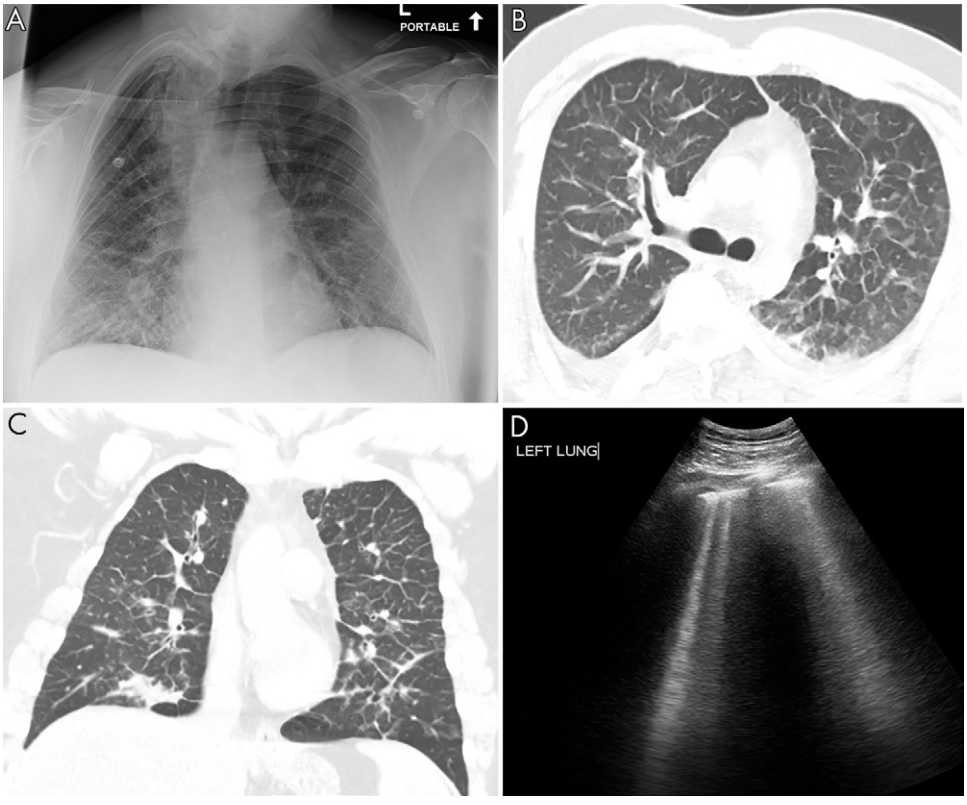

Figure 4: Pulmonary edema on lung US. *A*, Anteroposterior chest radiograph shows nonspecific prominent interstitial markings bilaterally in a 27-year-old man with pulmonary edema. *B*, Axial and *C*, coronal CT images show marked bilateral septal thickening, scattered consolidation, and ground-glass opacity. *D*, Lung US shows B-line artifacts arising from the pleural line and loss of A-lines. Movie 3 shows B-line artifacts in this same patient.

is becoming thickened and/or inflamed. Color Doppler imaging is useful for the evaluation of lung abscesses and empyema. A lung abscess demonstrates internal vascularity, because there are residual portions of the necrotic lung parenchyma in the lesion (Fig 10). In comparison, pleural-based empyema demonstrates no internal flow (Fig 11) (45). Foci of gas within a collection are

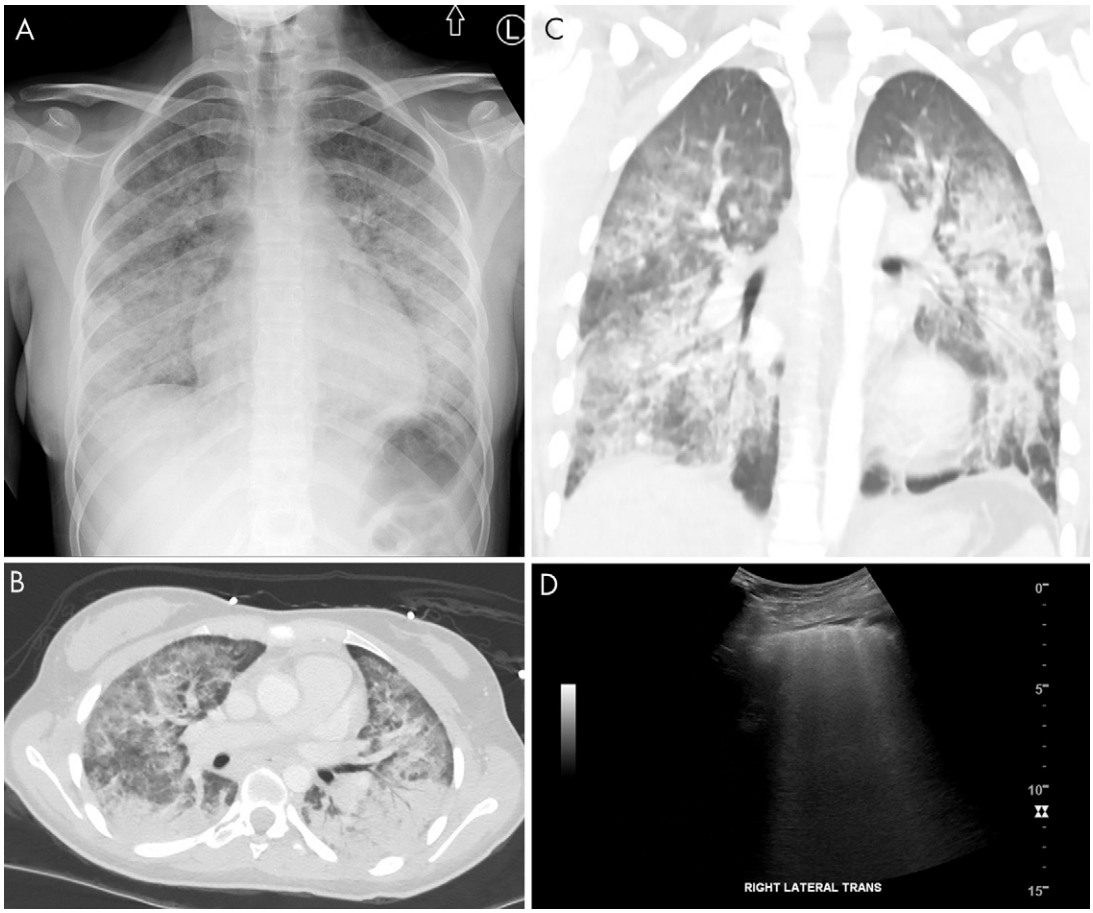

Figure 5: Vaping lung injury on lung US. *A*, Anteroposterior chest radiograph demonstrates nonspecific bilateral interstitial and consolidative pulmonary opacity in a 17-year-old adolescent girl with a vaping-induced lung injury. *B*, Axial and *C*, coronal CT images demonstrate diffuse bilateral consolidation, interstitial thickening, and ground-glass opacity. *D*, Lung US demonstrates loss of A-lines with confluent B-line artifacts better appreciated on the cine clip (Movie 4) Trans = transverse.

hyperechoic and demonstrate twinkle artifact on color Doppler US. Complex conditions containing mixed areas of pneumonia, atelectasis, and pleural fluid often are better assessed at lung US than at chest radiography (Fig 12).

Viral infections, including COVID-19 and bronchiolitis, can also be assessed and monitored using lung US (54,63–66). There is subjective enthusiasm for the ability of lung US to diagnose, stratify risk, and monitor COVID-19 infection, although findings at lung US can lack specificity (63). B-line artifact of varying severity, consolidations, and pleural irregularities have all been visualized in COVID-19 infection (Fig 13) (Movies 9 and 10). In areas of focal ground-glass opacity, diffuse confluent B-lines are present with loss of A-lines. Pleural effusion is rare in these patients. During the recovery phase, the B-lines decrease and the A-lines typically return. It is important to note that lung US performed on patients with COVID-19 presents a risk to the operator; this risk can be minimized with the proper use of protective equipment (63). Outside of COVID-19, lung US is effective in evaluating viral infection in pediatric patients (22,25,28,36).

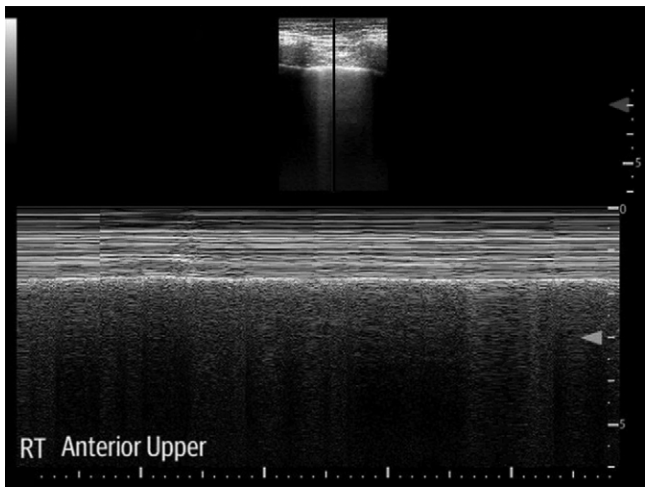

Figure 6: In healthy lung, M-mode US shows the seashore sign in which tissue superficial to the pleural line remains stationary creating smooth horizontal lines, and deep to the pleura, the lung motion interrupts the lines, creating a finely interrupted granular or "sandy" pattern. RT = right.

Future Directions and Medical-Legal Perspectives

As the use of lung US increases, diagnostic radiologists stand at a crossroads. Should we leave lung US to the clinicians? Or, perhaps, might we stake our own claim to the modality? We feel that there is a role for both clinicians and radiologists in performing and interpreting lung US. In general, lung US and

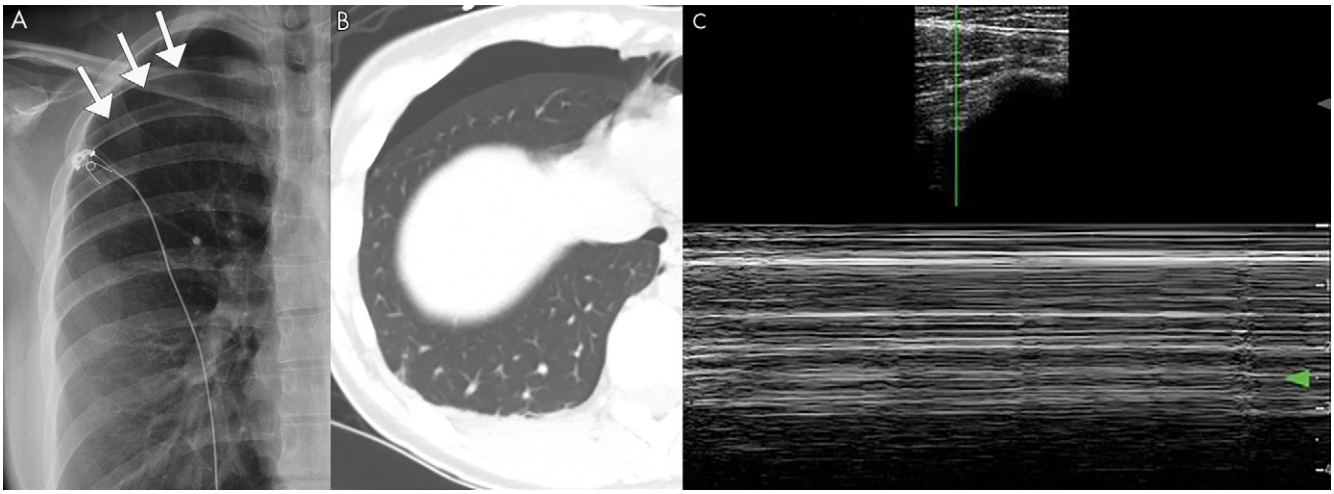

Figure 7: Pneumothorax on lung US. *A*, Posteroanterior chest radiograph and *B*, axial CT image of a spontaneous pneumothorax in a 26-year-old patient. *C*, M-mode US image shows the barcode sign, in which the smooth horizontal lines corresponding to the stationary chest wall are uninterrupted owing to lack of lung sliding, which is diagnostic for pneumothorax. Cine clips show absent lung sliding in the right lung (Movie 5) and the normal lung sliding in the left lung (Movie 6), which cannot be appreciated on still imaging. Arrows indicate location of the pleura in the setting of a pneumothorax.

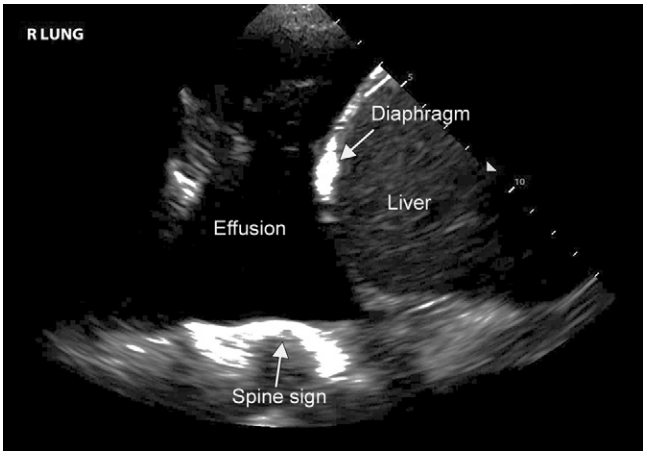

Figure 8: Pleural effusion on lung US. Lung US image of a patient with a moderate-sized pleural effusion. The acoustic window created by the effusion allows visualization of the spine (spine sign), as can be seen in this image. Normally, the vertebral bodies are not apparent on US.

chest radiography should be understood as complementary examinations, each providing unique clinical data with its own strengths and limitations. One could consider initially assessing patients with diagnostic lung US, because it is radiation-free, and then in cases of clinical uncertainty, follow up with radiography. However, the advantages of diagnostic US must be weighed against the increased time and personnel resources needed to perform and interpret lung US compared with those for routine chest radiography. Perhaps in children, for whom radiation is a greater concern, the benefits of lung US outweigh this drawback. Known infections, including pneumonias and viral illnesses, can be safely monitored with lung US, thus eliminating the need for repeat radiation exposure. As to who should perform and interpret lung US, there may be a role for both point-of-care examinations and more formal involvement by a radiologist. Given the time cost of a full lung US examination, routine use as a point-of-care screening tool in the emergency department may be best performed by clinicians. In more complicated cases, however, a radiologist may offer expertise that is best suited to a formal diagnostic examination.

As we embark into new territory with lung US, some concerns exist regarding the potential additional malpractice exposure to a clinician performing lung US. In general, point-of-care US is already in widespread use and is generally accepted (67). Review of the literature shows no known lawsuits related directly to point-of-care US; however, litigation has occurred secondary to the failure to perform US, which suggests that use of point-of-care lung US may reduce the risk of litigation (68,69). There are published professional standards for quality assurance, archiving, and documenting US procedures that should be followed (70,71).

With the recent improvements in point-of-care portable US, lung US has the potential to replace the stethoscope at the bedside (11,14,72). Auscultation often has limited sensitivity and specificity, and US allows for a focused examination of the area of interest (73). Another obvious application of lung US is in rural or economically impoverished areas, where access to medical imaging may be limited, and in low- and middle-income countries where the modality has already demonstrated efficacy (74). Similar to other uses for US, lung US is also well-suited to tele-US and remote reading (75–77). Because pneumonia is the leading killer of children from birth to 5 years of age worldwide, with nearly 1 million associated deaths per year and over 100 million hospitalizations per year, the use of lung US could be a powerful tool in promoting global health for aid organizations (74,78–83).

For years, chest radiography and chest CT have been the staples of regular thoracic diagnostic imaging. As a versatile and highly accurate imaging modality, lung US has the potential to substantially alter the thoracic diagnostic imaging milieu for the better. With its high sensitivity and specificity for a variety of pulmonary conditions, lung US appears to have a bright future, and its increasing use has the potential to positively affect health care worldwide.

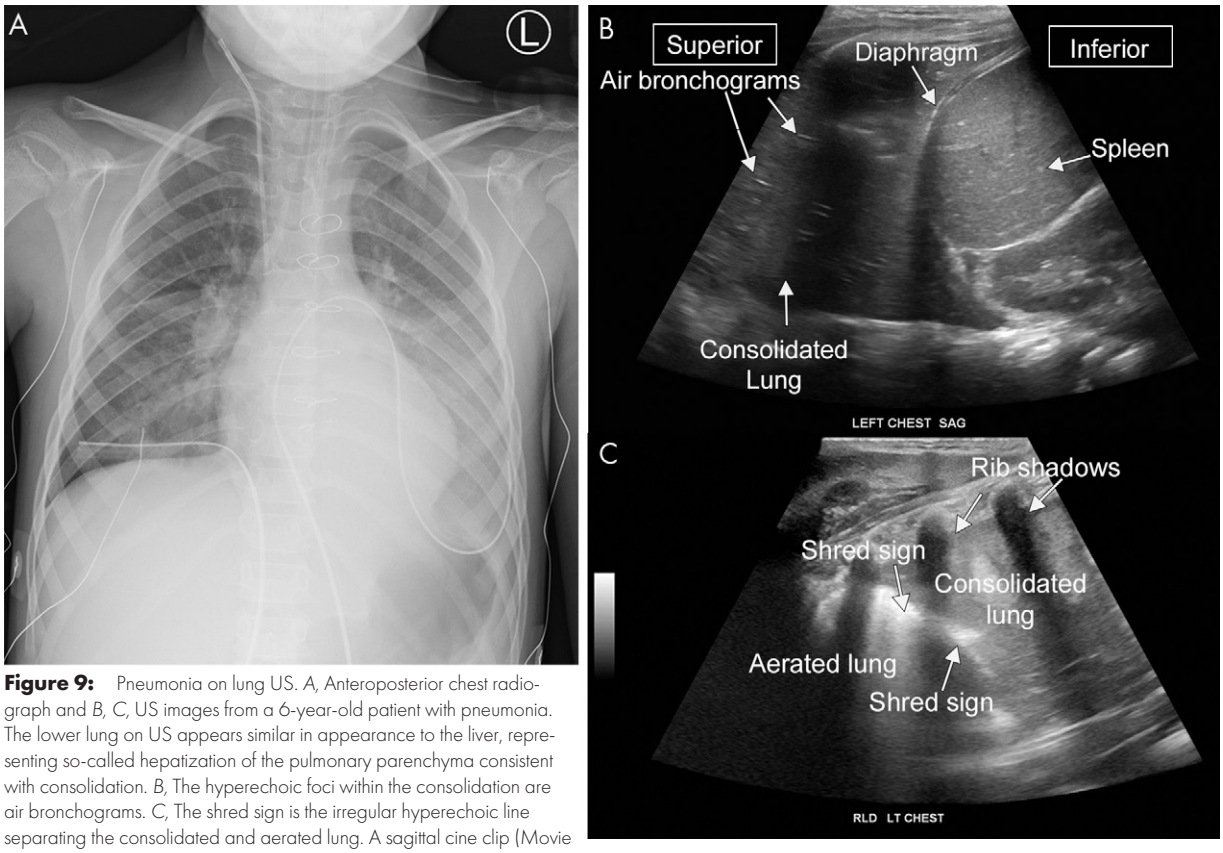

Figure 9: Pneumonia on lung US. *A*, Anteroposterior chest radiograph and *B*, *C*, US images from a 6-year-old patient with pneumonia. The lower lung on US appears similar in appearance to the liver, representing so-called hepatization of the pulmonary parenchyma consistent with consolidation. *B*, The hyperechoic foci within the consolidation are air bronchograms. *C*, The shred sign is the irregular hyperechoic line separating the consolidated and aerated lung. A sagittal cine clip (Movie 7) and a transverse cine clip (Movie 8) show more detail. LT = left, RLD = right lateral decubitus.

Acknowledgments: We would like to thank Solomon Kim, Nadezhda Kiriyak, Sarah Klingenberger, Jane Lichorowic, and Gwen Mack for their assistance with our illustrations and figures. We would like to thank Nancy Carson, MBA, RDMS, RVT, for her manuscript edits.

Author contributions: Guarantor of integrity of entire study, K.A.K.J.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; approval of final version of submitted manuscript, all authors; agrees to ensure any questions related to the work are appropriately resolved, all authors; literature research, T.J.M., D.J.R., Y.TZ., T.P.O., K.A.K.J.; clinical studies, J.W.; and manuscript editing, all authors

Disclosures of Conflicts of Interest: **T.J.M.** disclosed no relevant relationships. **D.J.R.** disclosed no relevant relationships. **Y.T.Z.** disclosed no relevant relationships. **J.W.** disclosed no relevant relationships. **T.P.O.** disclosed no relevant relationships. **W.H.N.** disclosed no relevant relationships. **K.A.K.J.** disclosed no relevant relationships.

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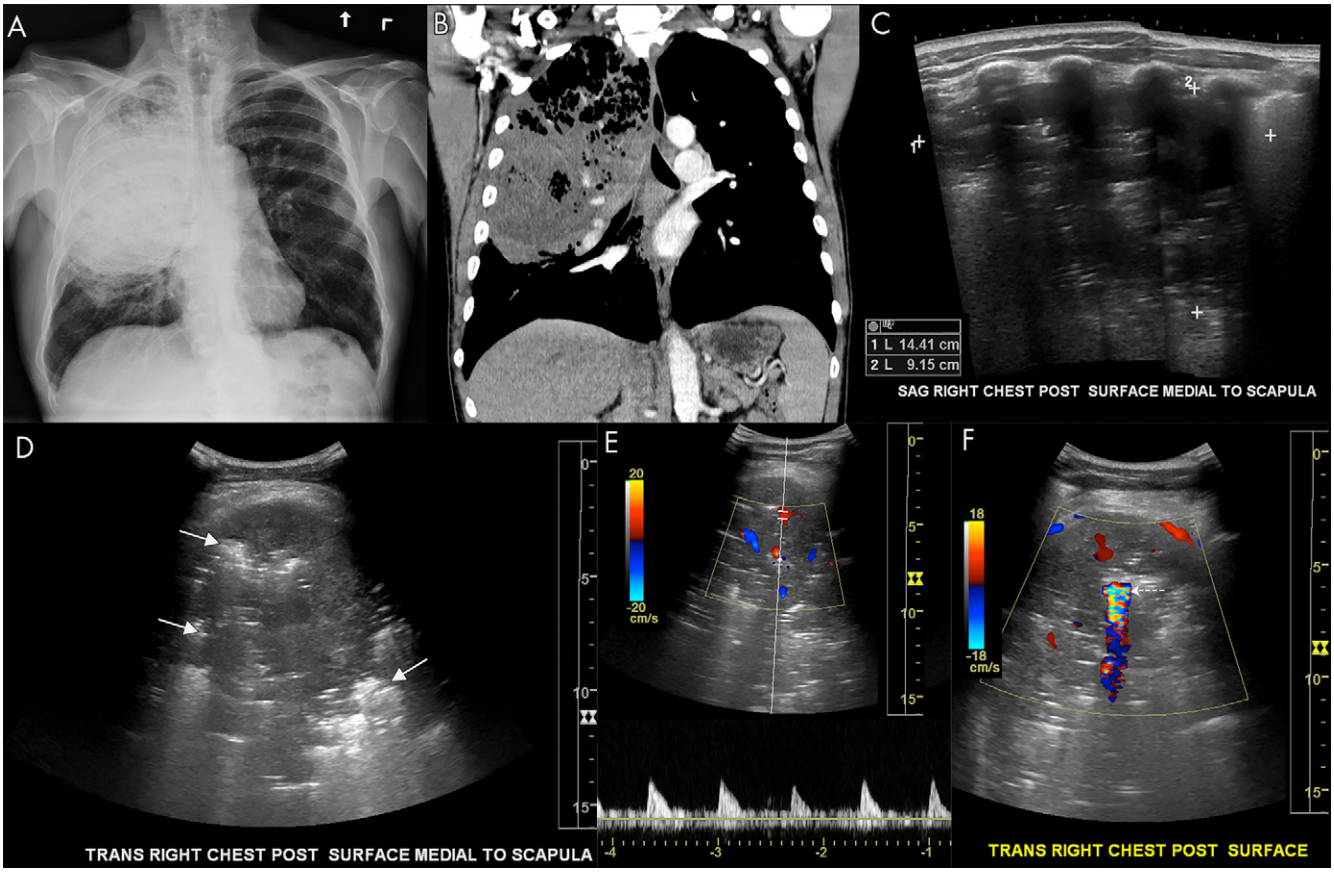

Figure 10: Pulmonary abscess on lung US. *A*, Anteroposterior chest radiograph and *B*, coronal chest CT image show a large pulmonary abscess in the right upper lung containing foci of air in a 56-year-old smoker. *C*, Sagittal and *D*, transverse grayscale US images demonstrate a large 14-cm abscess. Hyperechoic foci are seen throughout the abscess corresponding to air (arrows, *D*). *E*, *F*, Associated color Doppler images show internal Doppler flow consistent with abscess. There is a large focus of twinkle artifact corresponding to air within the abscess (dashed arrow, *F*).

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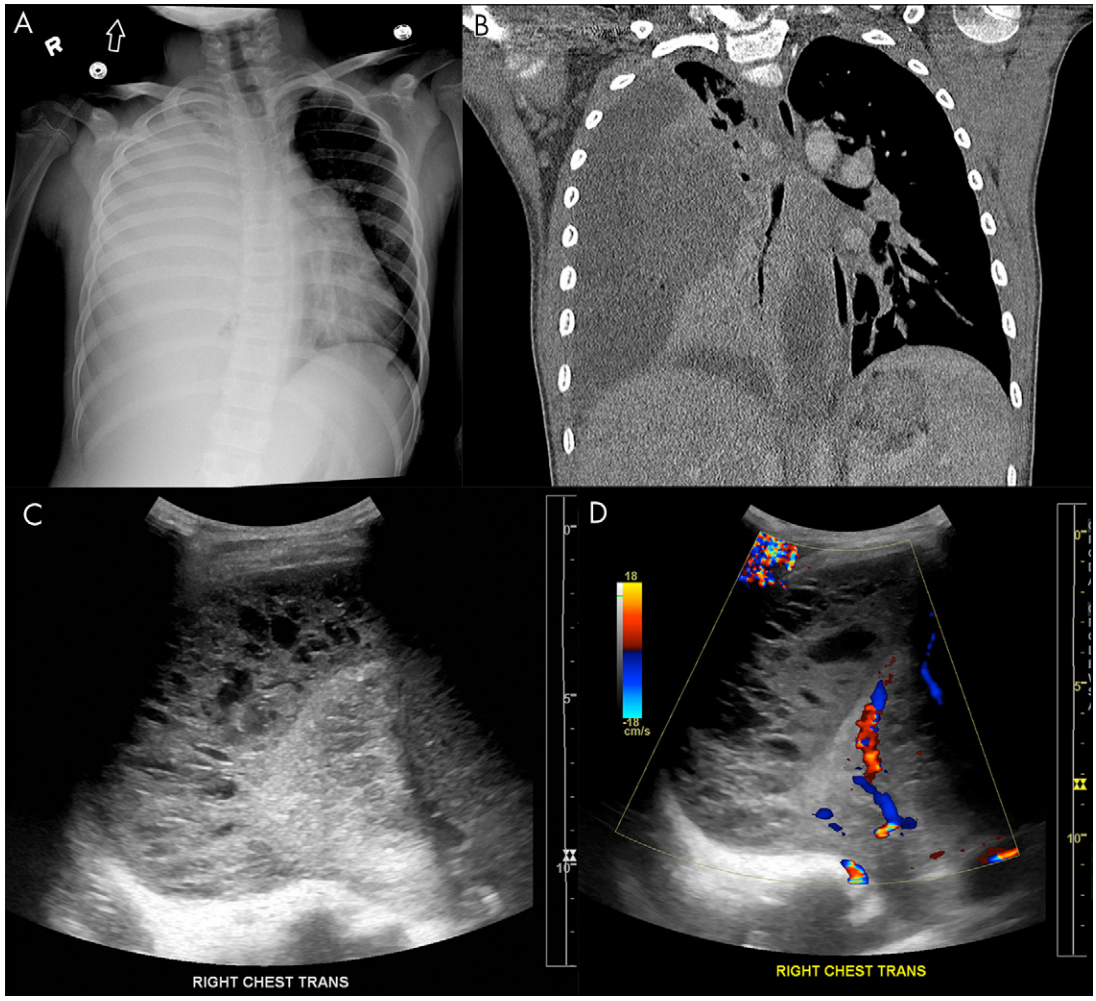

Figure 11: Empyema on lung US. *A*, Anteroposterior chest radiograph and *B*, coronal chest CT image show a large, right-sided empyema occupying the pleural space with associated compression of the pulmonary parenchyma in a 9-year-old boy. Lung US *C*, grayscale and *D*, Doppler images demonstrate a multiloculated complex-appearing fluid collection in the pleural space with septations and internal debris without internal color flow.

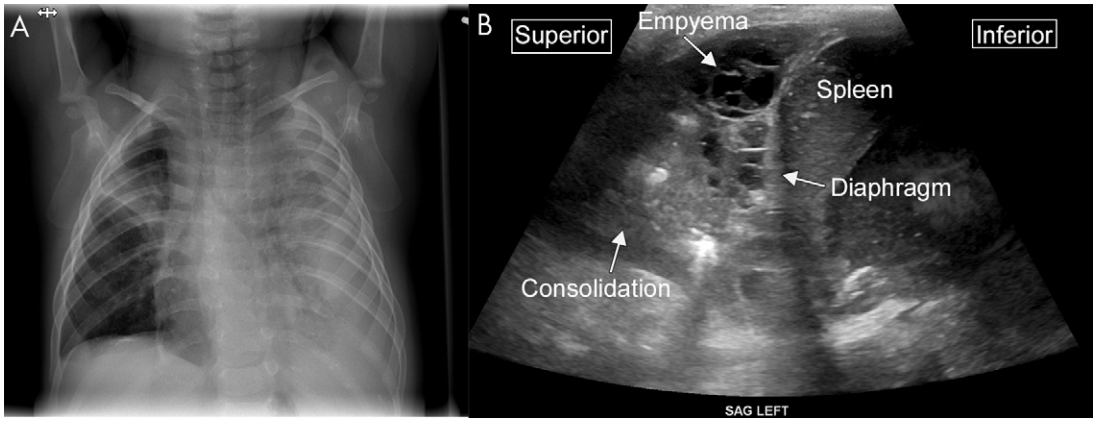

Figure 12: Complex collection on lung US. *A*, Anteroposterior chest radiograph demonstrates near complete opacification of the left hemithorax, with loculated pleural fluid tracking along the left lateral chest wall in an 8-month-old male infant. In addition, a focal consolidation is present in the right upper lobe. *B*, Sagittal US image from the same patient shows consolidation within the lung and a multiseptated complex pleural fluid collection consistent with empyema.

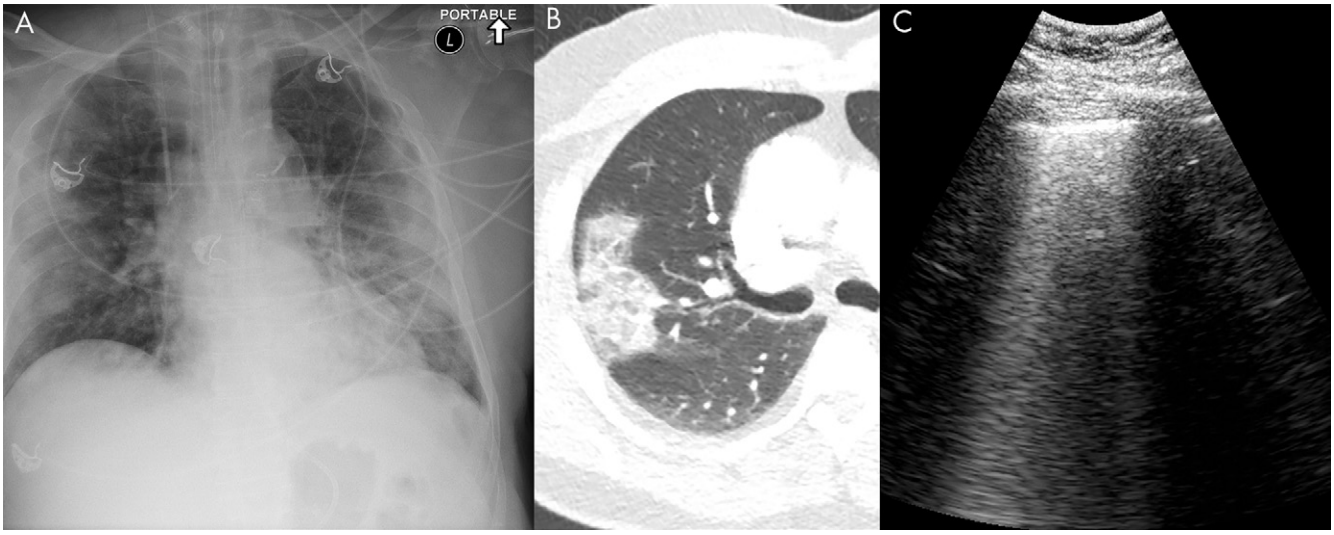

Figure 13: COVID-19 infection on lung US. *A*, Anteroposterior chest radiograph, *B*, axial chest CT image, and *C*, lung US image from the same 74-year-old man, who tested positive for COVID-19 5 days prior to imaging. The chest radiograph shows bilateral peripheral opacity, which presents with a ground-glass appearance on the chest CT image. Lung US imaging in this patient demonstrated numerous B-lines throughout the parenchyma which were diffusely confluent in some sections. These are better seen in a cine clip (Movie 9). A small consolidation in a patient with COVID-19 is shown in Movie 10.

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